International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249–6890; ISSN(E): 2249–8001
Vol. 10, Issue 2, Apr 2020, 1331–1340

RESEARCH ON THE ESTIMATION OF NATURAL FREQUENCY OF MECHANICAL STRUCTURES, MACHINES, AUTOMOBILES AND BIO-SYSTEMS

SAYEL M. FAYYAD[1], ABDEL SALAM ALSABAGH[2] & MOHANNAD O. RAWASHDEH[3]

[1]*Associate Professor, Department of Mechanical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University, Amman - Jordan*

[2]*Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering Technology, Al-Balqa Applied University, Amman - Jordan*

[3]*Assistant Professor, Department of Mechanical Engineering-Autotronics, Faculty of Engineering Technology, Al-Balqa Applied University, Amman - Jordan*

ABSTRACT

This paper represents a developed method for the measurement of natural frequencies of some suggested structures, which may be used later in measuring the vibrational behavior of such mechanical structures, machinery, automobiles, vehicles and some other applications in bio-systems such as human body and interconnected systems. This developed method is based on the measurement of the two main physical quantities required to calculate the natural frequency of any system: mass (M) and stiffness (K). These measurements include some mechanical systems and structures as well as biological systems such as the human body or some organs of the human body. It has been found that coefficients such as age, mass and rigidity of many systems have significant effects on the natural frequencies of various mechanical systems and its related machines and automobiles. Results show that increasing human body not only lowers the natural frequency, but also makes the body weak in facing external vibrations. On the other hand, increasing the human body stiffness values (K) eventually increases natural frequency values and so the human resistance to external vibrations increases, this is also true for machines frames.

KEYWORDS: Bio-Systems, Automobiles, Mechanical Structures, Mechanisms, Natural Frequency & Vibrations

Received: Oct 24, 2019; **Accepted:** Nov 14, 2019; **Published:** Apr 11, 2020; **Paper Id.:** IJMPERDAPR2020127

Original Article

1. INTRODUCTION

Natural frequency is a very important assessment for the structural behavior for wide range of systems; it reflects its behavior and its response to many external forces. The natural frequency can be defined as the frequency in which the system oscillates when it is disturbed in the absence of external forces. The importance of the natural frequency is noticed here for many reasons; firstly, all kind of structures in the universe have their own natural frequency. Secondly, the natural frequency of any object is the key to control its vibrational behavior. Furthermore, the created wave types of an object will be known by defining its vibration behavior.

The main objective of this paper is to investigate a novel measuring tool for assessing the natural frequency of some mechanical systems and bio structures like human bodies. It is important to emphasize that the natural frequency is a unique property for each human body or by other words no two persons have the same natural frequency, this is mostly like a unique finger print of or the genetic DNA code. In general, vibrations have a great effect on the human body. It is extremely important to properly calculate the natural frequency for an organic machine or structure to avoid failure leading to excessive devastation consequences

due to the well-known resonance phenomenon which occurs when natural frequency coincides with an external excitation frequency, leading to failure due to sudden increase in the amplitude ratio [1]. Mechanical vibrations have direct effects on human body, mechanical systems, machines, automobiles and different structures. These excessive vibrations can cause cracks, damage, or even failure. Figure (1) shows the failure occurred to Tacoma Bridge in 1940 because of reaching the bridge structure to resonance. Since these consequences are unavoidable, there must be standard procedure in the design and development for most, if not all engineering systems [3].

Figure 1: Tacoma Narrows Bridge During Wind-Induced Vibration. (Farquharson Photo, Historical Photography Collection, University Of Washington Libraries-Rao) [3].

There are little papers dealt with such issue, most of previous works were focused on the effects of vibrations on the human body. The natural frequencies for some organs of the human body was estimated especially for organs and organs of the child's body, some data was also gathered based for adults in [1]. It was also stated in [2] that each individual organ has its own natural frequency which can resonate with vibrational energy received and coherent with their natural frequencies. Whole Body Vibration (WBV) can be the reason behind resonance occurs to the human body or its organs. The changes in the natural frequency characteristics of the trunk during exposure to seated whole-body vibration was studied by [4], It was found that the whole-body vibration causes a decrease in natural frequency leading to a decrease in the trunk stiffness, the study also shows an increase in the peak amplitude of the frequency response functions resulting in a decrease of the overall trunk damping. The traditional vibrational mass– spring–damper models including one-body and multi-body models were addressed by [5], the aim of the study was to determine different modeling values affected the model. Seated human body/seat for a multi-degree freedom lumped systems during vibration were investigated to obtain their dynamic characteristics, the suggested model provided theoretical tool for human body-dynamics research. The authors also suggested a model which may be further used to develop design guide tool for a composite cushion using the principle of quasi-uniform body/seat contact force distribution [6]. A vibrational analysis of a multi degree of freedom system (DOF) excited by using

harmonic force in the time and frequency domain was performed in [11]. An Arduino microcontroller was used to study as an acquisition system and low-cost Micro Electromechanical Systems (MEMS) accelerometers for the instrumentation of the system. The multi (DOF) systems were studied for a large number of problems in different mechanical models by [11]. A new method to measure the natural frequency of a blade using Artificial Neural Networks (ANN) was proposed in [12]. The resonance of the honeybees' wing was tested whether if it matches the wing beat frequency, against the 'stiff element' hypothesis that the wing's first longitudinal mode exceeds the wing beat frequency [13]. In this research, the natural frequency of solid structures like automobiles and bio-systems like human body is calculated using a simple principle of determining the equivalent mass of the structure or element and the equivalent stiffness value of such structures, and finally applying the formula of determining the natural frequency which is the squre root of K_{equ} by M_{equ}.

2. MATERIALS AND METHODS

Based on the theory of the strength of materials, the longitudinal and bending stiffness of a beam or bar elements depends on the modulus of longitudinal elasticity (Young's modulus, E). For tension, the specific stiffness K is defined as:

$$K = \frac{E.A}{L} \tag{1}$$

Where A is the cross-sectional area (m^2), E is the modulus of elasticity of the material (Pa) and L is the length of the element. For unity length, equation (1) becomes:

$$K = E.A \tag{2}$$

The natural frequency can defined as:

$$w_0 = \sqrt{\frac{K}{M} - (C/2M)} \tag{3}$$

Where C is the damping coefficient which is neglected here. So, the natural frequency for any system or mechanism or bio-system (which is generally composed from more than one element) can be given as:

$$w_0 = \sqrt{\frac{K_{equ}}{M_{equ}}} \tag{4}$$

Where K_{equ} is the equivalent stiffness coefficient (or equivalent spring constant) for all elements of the system or structure, M_{equ} is the equivalent mass of the system. So once K_{equ}, and M_{equ} of some mechanical element or structure are calculated or measured the natural frequency is easily determined. Finding equivalent stiffness (K_{equ}) depends strictly on calculating the potential energy of the system i.e. P.E, while equivalent mass (M_{equ}) of any system depending on determining the kinetic energy of the system.

As an example, let us take the following mechanical system as shown in Figure 2.

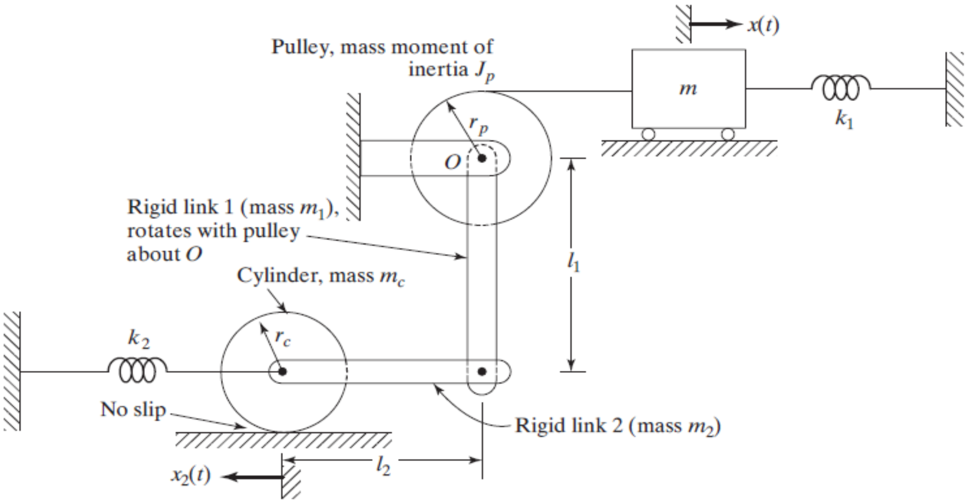

Figure 2: Mechanical System [3]

To find the equivalent mass: the kinetic energy (T) of the system is calculated which can be written as

$$T = \frac{1}{2} m x^2 + \frac{1}{2} J_p \theta^2 + \frac{1}{2} J_1 \theta_1^2 + \frac{1}{2} m_2 x_2^2 + \frac{1}{2} J_c \theta_c^2 + \frac{1}{2} m_c x_2^2 \tag{5}$$

This gives an equivalent mass as:

$$M_{equ} = m + \frac{J_p}{r_p^2} + \frac{1}{3} \frac{m_1 l_1^2}{r_p^2} + \frac{m_2 l_1^2}{r_p^2} + \frac{1}{2} \frac{m_c l_1^2}{r_p^2} + m_c \frac{l_1^2}{r_p^2} \tag{6}$$

Where *m* is the mass, *J* is the polar moment of inertia, *r* is the radius, *l* is the length, *x* is the displacement and *Θ* is the angular displacement. The equivalent stiffness constant K_{equ} for this system is calculated by using potential energy of the system. Then the natural frequency of the system can be determined easily using equation (4).

For a human body or bio-systems, the same procedure is followed i.e. if the mass of the human is determined using any method like using simply some balance or weighing system which considered as M_{equ}, and if the stiffness of the body is calculated or measured which is considered as K_{equ}, then the natural frequency of the body can be calculated using equation (4) too.

2.1 Methods of Natural Frequency Measurements

There are many methods, techniques, and devices to measure natural frequency of mechanisms, systems, structures, and bio-systems including human bodies. Some of these methods include: Evaluation method using Fourier series: this method using Modal analysis is the method used most frequently in laboratory applications. The transfer function of the component is used for determining the natural frequencies of the element [7]. The second method is stimulation method: which causes the test object to vibrate at its resonance frequency. This method uses sensors and then records these vibrations. The method also permits the natural frequencies to be determined rapidly and the decay behavior to be evaluated. Figure 3 shows the most common method of simulation. In this method, a simulating device is used in which a modal hammer uses a quartz force sensor on the beating side of the head of the hammer; the sensor measures the force during the striking [8].

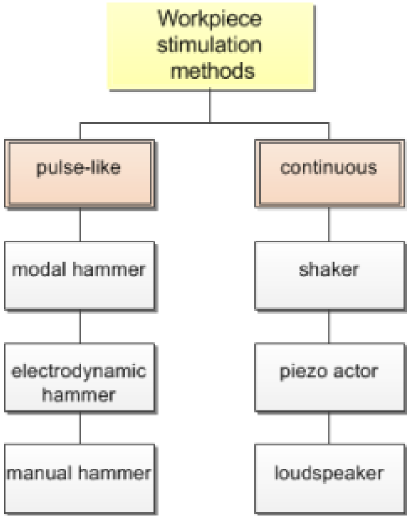

Figure 3: Noise Method to Determine Natural Frequency [8]

3. MODELING RESULTS AND DISCUSSIONS

3.1 The Suggested Methods

3.1.1 Direct method

The suggested method is summarized by the following flow-chart:

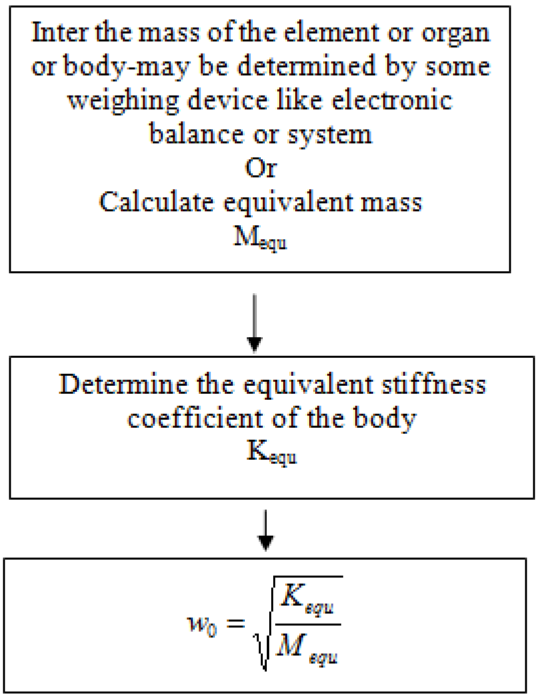

Figure 4: Flow-Chart to Calculate the Natural Frequency of any Body.

For example, for a human leg of 78 kg mass, the stiffness constant of the leg is 28500 N/m [5]; the natural frequency was calculated to be 19.11 rad/s. If the human body is simulated to be a collection of springs, dampers and masses are shown in Figure 5.

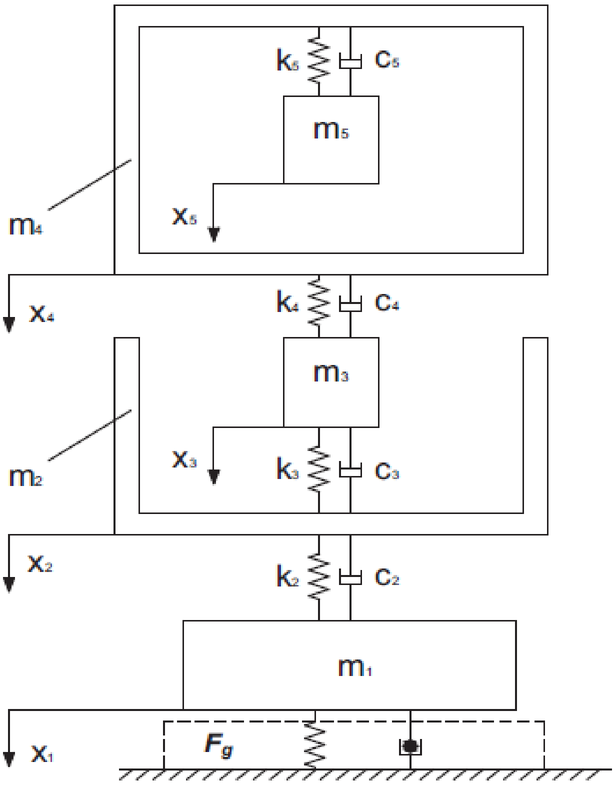

Figure 5: Case-Study of Human Body Simulation.

To calculate the natural frequency of each organ of the body model, mass and stiffness values are needed. The suggested values of m's and k's are taken to be as follows: m_1 = 1.8 kg, k_2 = $1x10^5$ N/m, m_2 = 6.3 kg, k_3=50N/m, m_3 = 5.4 kg, k_4=75 N/m, m_4 = 22.5 kg, k_5=10 N/m, and m_5=54 kg. [5] (All damping values are neglected for healthy human body). The natural frequency for each organ is calculated in table 1 below.

Table 1: Natural Frequencies of the Studied Model

Mass (kg)	k(N/m)	w_0(rad/s)
m_2=6.3	k_2=100000	125.98
m_3=5.4	k_3=50	3.04
m_4=22.5	k_4=75	1.83
m_5=54	k_5=10	0.43

To calculate the total human body, natural frequency modeled is shown in Figure 5. Both equivalent mass and stiffness are required. After calculations, it is found that the natural frequency of human body depends on mass of each body organ and its stiffness, the values ranged from 0.5 Hz to 1000 Hz. If an average person of 60 kg (depending on its kinetic energy) is taken and if its equivalent stiffness i.e. K_{equ}=50000N/m (depending on its potential energy) then its natural frequency is equal to 28.86 rad/s. For example, the human brain has a natural frequency ranging from few Hz to 20 Hz body and skin has a frequency of 1000 Hz [5, 6]. External vibrations affects human body, but this depends on the organ affected and the frequency of the external effect, which may cause what so called resonance, i.e. the maximum value of frequency received by the organ of the body or the external frequency reaches the value of the natural frequency of the organ. Figure 6 shows some values of resonance frequency of the human body and some calculated values of natural frequency or resonance frequencies (which represents the maximum value of Natural Frequency) of human body organs.

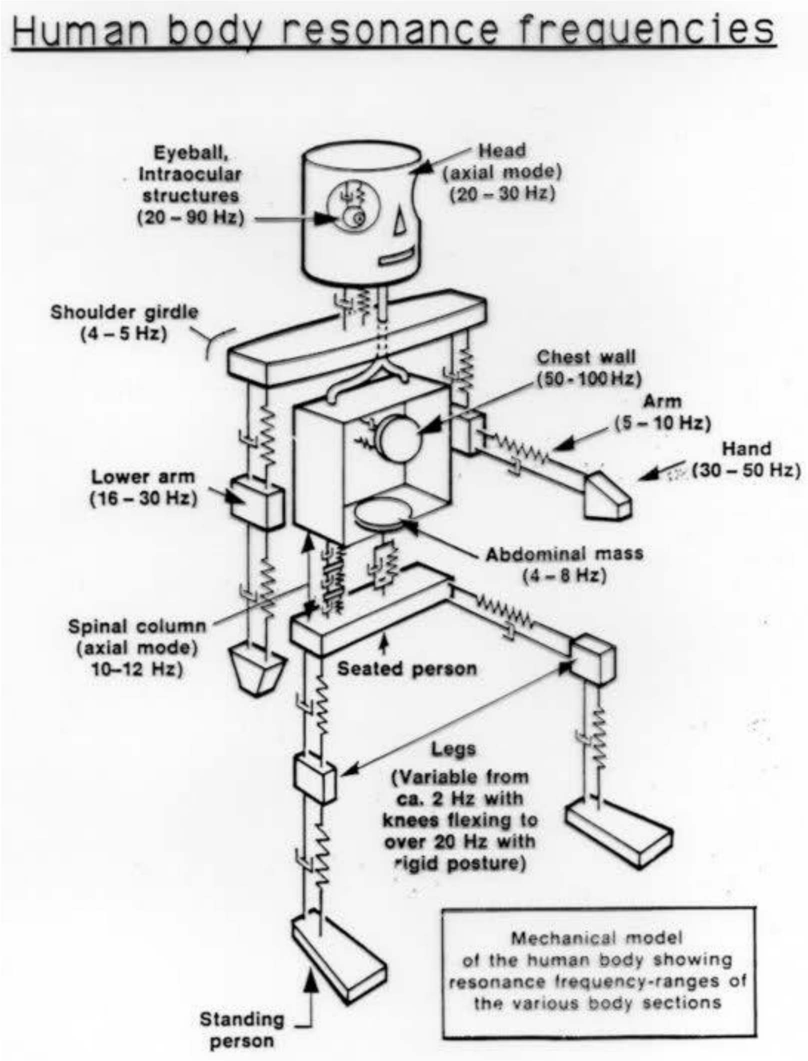

Figure 6: Natural Frequency Values of Some Human Body Organs.

3.2 Some Effects of Vibrations on Human Body

The transmission of vibration to the human body at the natural frequency as a whole or of its individual organs will result in resonance. It will make the body or an organ of the body vibrate at a magnitude greater than that of applied vibratory force like vibrations exposed on drivers of automobiles and passengers from the car vibrations. Vibrations have effects on the head, back and neck, and vehicular jarring [9-10].

3.3 Parameters affect on the Natural Frequency of Human Body:

Three main parameters affect the human body's natural frequency: age, mass, and stiffness coefficient of its organs. If the equivalent mass of the human body increases, then the natural frequency of the whole body decreases, age affects both mass and stiffness of the human body. The main parameter is the equivalent stiffness constant of the human body which represents the resistance of the body or structure to external loads or frequencies. It is noticed that as the stiffness constant of the human body increases, the natural frequency increases, and so the external vibration value which will cause resonance to human body organs affected by such vibrations increase. Figure 7 shows the relation between natural frequency values for different stiffness constants at a fixed average mass of human body taken at 70 kg as an average

value.

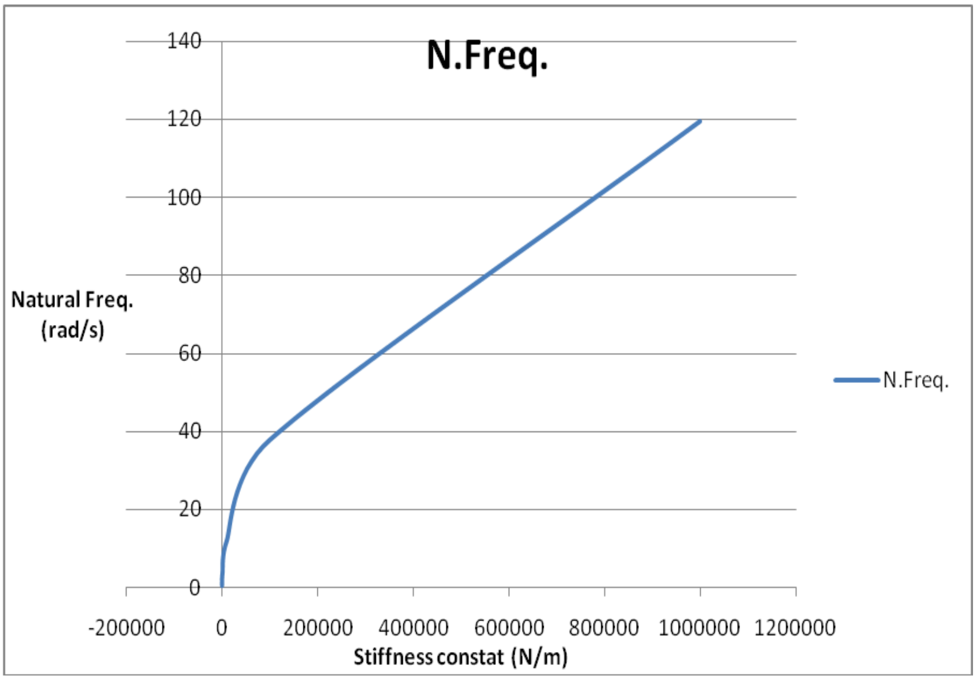

Figure 7: Natural Frequency of Human Body as a Relation with Stiffness Coefficent.

Figure 8 shows the natural frequency values of the human body as a related to the equivalent mass of the body calculated at constant stiffness of 10 kN/m. It can be noticed that as the mass increases, the natural frequency of the human decreases i.e. the more stiffness body values against less weight or mass have higher values of natural frequencies like sport players, while those persons have more mass (fatty humans) and low stiffness (for non-athletic people), this shows how an active life is important to increase the values of natural frequencies.

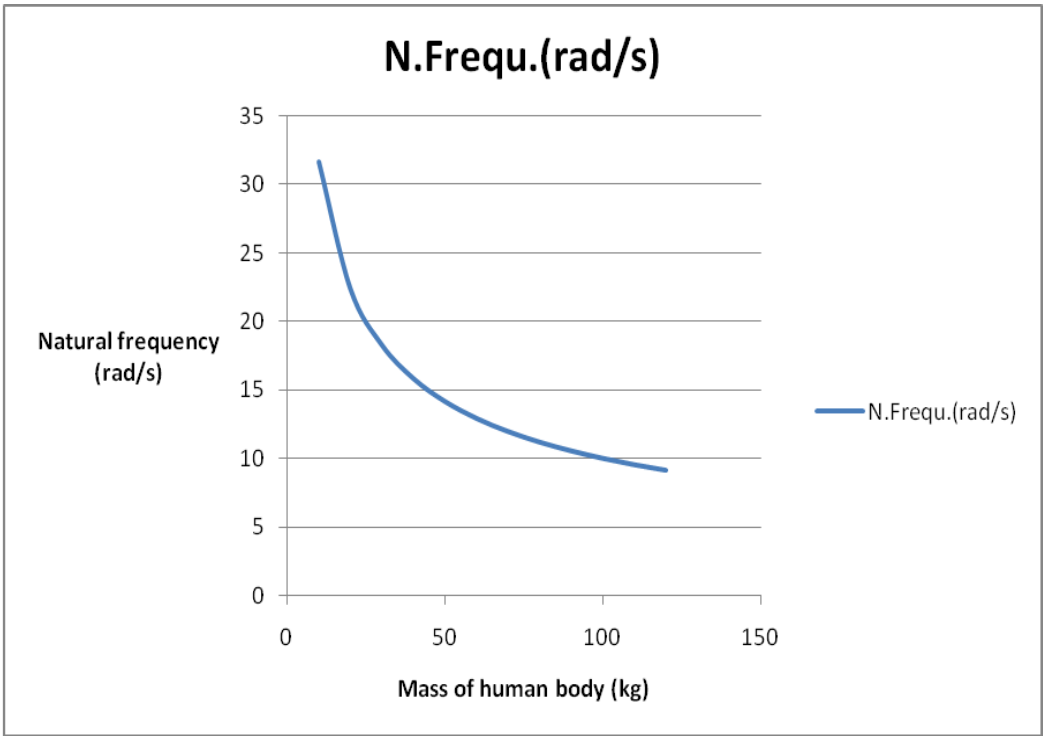

Figure 8: Natural Frequency of Human Body as a Relation with Mass.

4. CONCLUSIONS

In this work, the natural frequency of some mechanical structures such as cars, machines, and bio-systems is studied, analyzed, and calculated. The proposed measurement system is directly dependent on the calculation of both the equivalent mass and the stiffness of the human body and other mechanical structures. The effects of vibrations on the human body and machines are studied which may cause resonance for certain organs. Factors affecting the natural frequency values of organs of the human body are also analyzed. It has been found that the age, mass, and stiffness values of the human body organs affect greatly in the final values of the natural frequency of the human body and other mechanical structures like automobiles, mechanisms, machines and civil structures.

REFERENCES

1. *Dariusz W., 2006, "An Attempt to Estimate Natural Frequencies of Organs of the Child's Body", Automotive Industry Institute, Simulation Tests Laboratory, 55 Jagiellońska Street, 03-301 Warszawa, e-mail: d.wieckowski@pimot.org.pl.*
2. *Helmut W. and Alan G. M., 2011, "Whole-Body Vibration Building Awareness in SH&E", Professional Safety Journal, APRIL issue. www.asse.org.*
3. *Gregory P. S., 2008, "Effects of Seated Whole-Body Vibration on Spinal Stability Control", Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University, November 14th. Blacksburg, Virginia.*
4. *Nikooyanz A. and Zadpoor A., 2011, "Mass–spring–damper modeling of the human body to study running and hopping" – An overview Proc. I. Mech. E. Vol. 225 (Organ H): J. of Engineering in Medicine.*
5. *"Jacob R., and Mircea A., 2003, "Modeling the Human Body/Seat System in a Vibration Environment". Journal of Biomechanical Engineering, Vol. 125 (2-23).*
6. *Tomáš H., Jozef B., Kristína M., 2012, "Frequency analysis of acoustic signal using the Fast Fourier Transformation in MATLAB", Procedia Engineering Vol. 48. pp: 199 – 204.*
7. *Randall M., Matthews R., and Stiles M., 1997, "Resonant frequencies of standing humans", Ergonomics, Vol. 40 (9), pp: 879-886.*
8. *"Optimization and Modelling of Equilizing Flow Globe Valve for Structural Integrity Against Fluidic Loads." IMPACT: International Journal of Research in Engineering & Technology (IMPACT: IJRET), vol. 4, no. 8, pp. 13–18.*
9. *Matsumoto Y., Griffin M. J., 1998, "Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude", Journal of Sound and Vibration, Vol. 212, No. 1. pp. 85-107.*
10. *Ellis B. R., and Ji T., 1997, "Human-structure interaction in vertical vibrations, Structures and Building", Proceedings ICE, 122, pp.1-9.*
11. *Marcus V., Anderson L. Silva, Arthur G. Mereles, 2018, "On mechanical vibration analysis of a multi degree of freedom system based on Arduino and MEMS accelerometers", Revista Brasileira de Ensino de F´ısica, vol. 40, no. 1.*
12. *Sudhakar G., Jean-Claude L., Jan-O., 2016, "Detection of ice mass based on the natural frequencies of wind turbine blade", Wind Energy. Sci. Discuss., doi:10.5194/wes-2016-30.*
13. *Christopher J., Andrew M., Emily M., and Damian O., 2017,"Resonance frequencies of honeybee (Apis Mellifera) wings", Journal of Experimental Biology Vol.(2017), No. 220, pp.: 2697-2700 doi:10.1242/jeb.154609.*